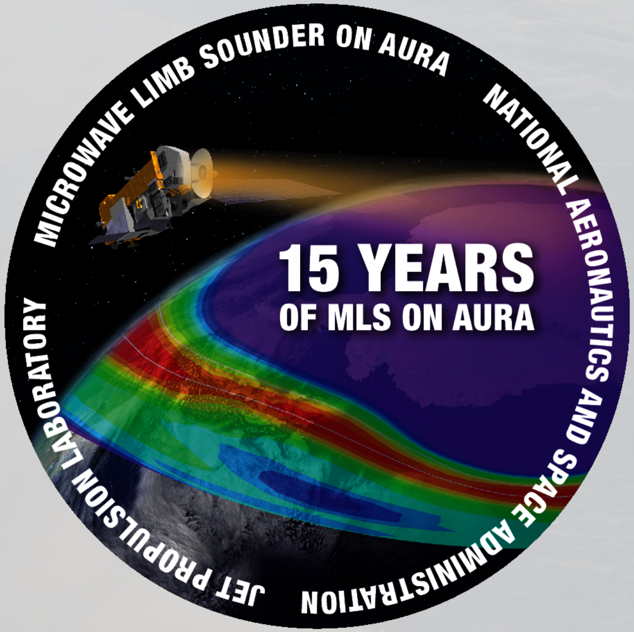
Aura Science Team Meeting 2019
Microwave Limb Sounder (MLS) update



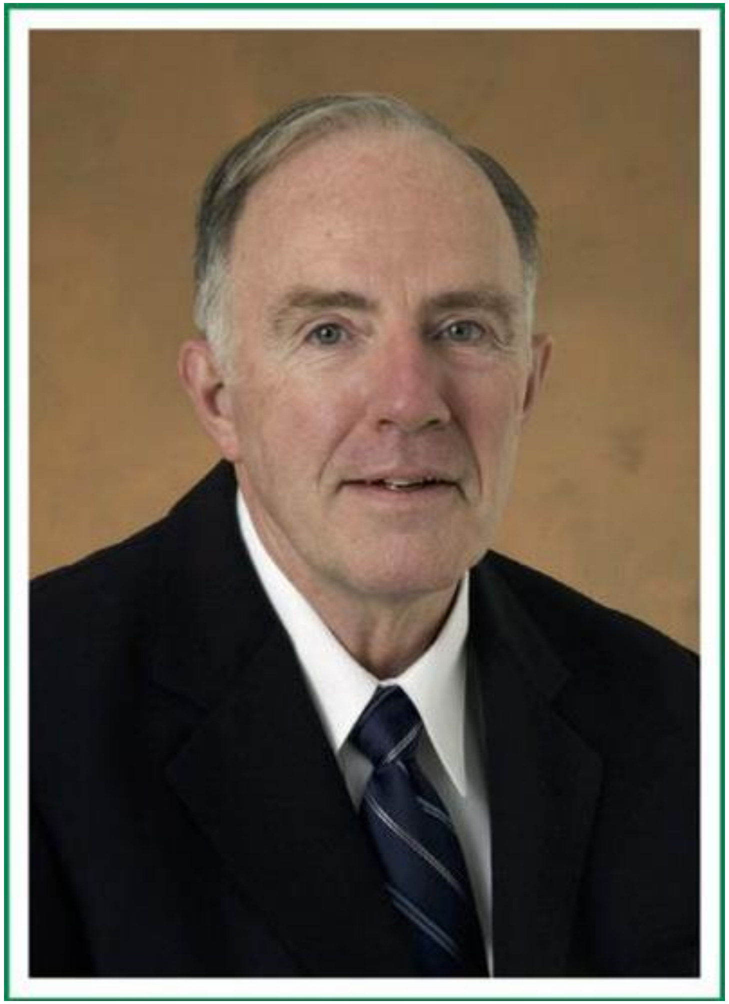
Nathaniel Livesey
Jet Propulsion Laboratory,
California Institute of Technology
on behalf of the entire MLS team

Photograph by ISS astronaut Ron Garan

Outline

- Reminder of MLS science targets, products, and instrument
- Review of recent MLS instrument performance
- Update on MLS “Version 5” algorithms
- Other MLS-related datasets and projects
- Selected recent science highlights
- Outlook for MLS and MLS-type measurements and instruments

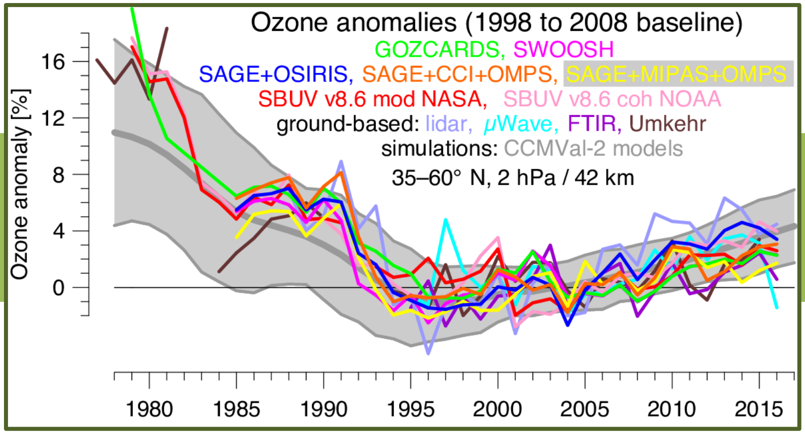
Herb Pickett 1943–2018

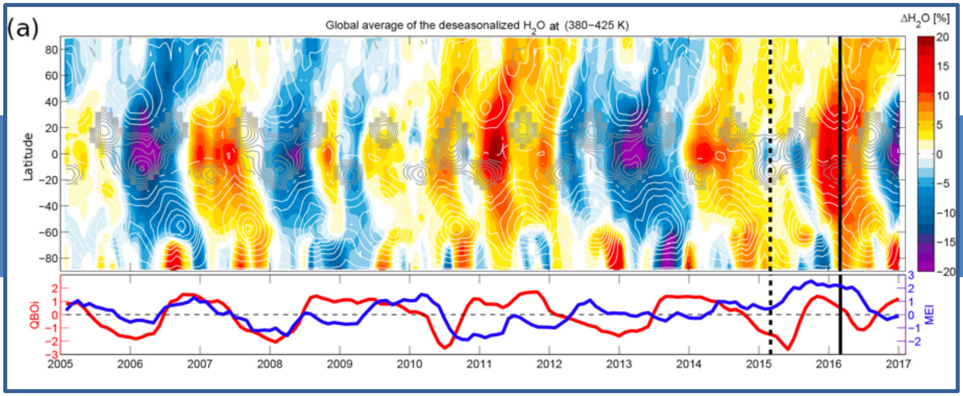


MLS science goals

Track ozone layer stability

Steinbrecht et al., ACP, 2017



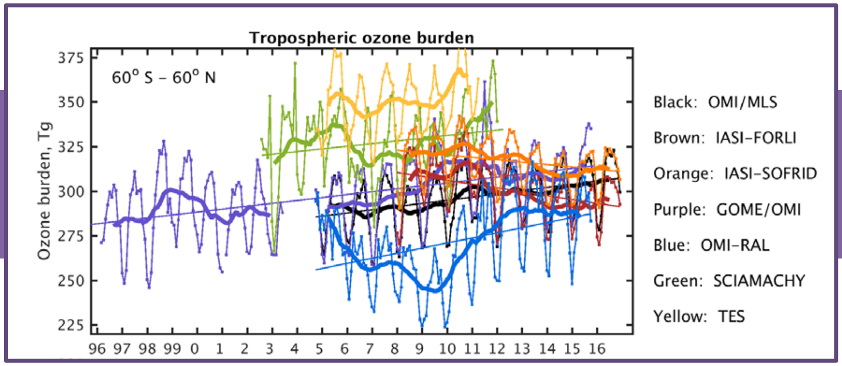


Quantify aspects of climate and composition interaction

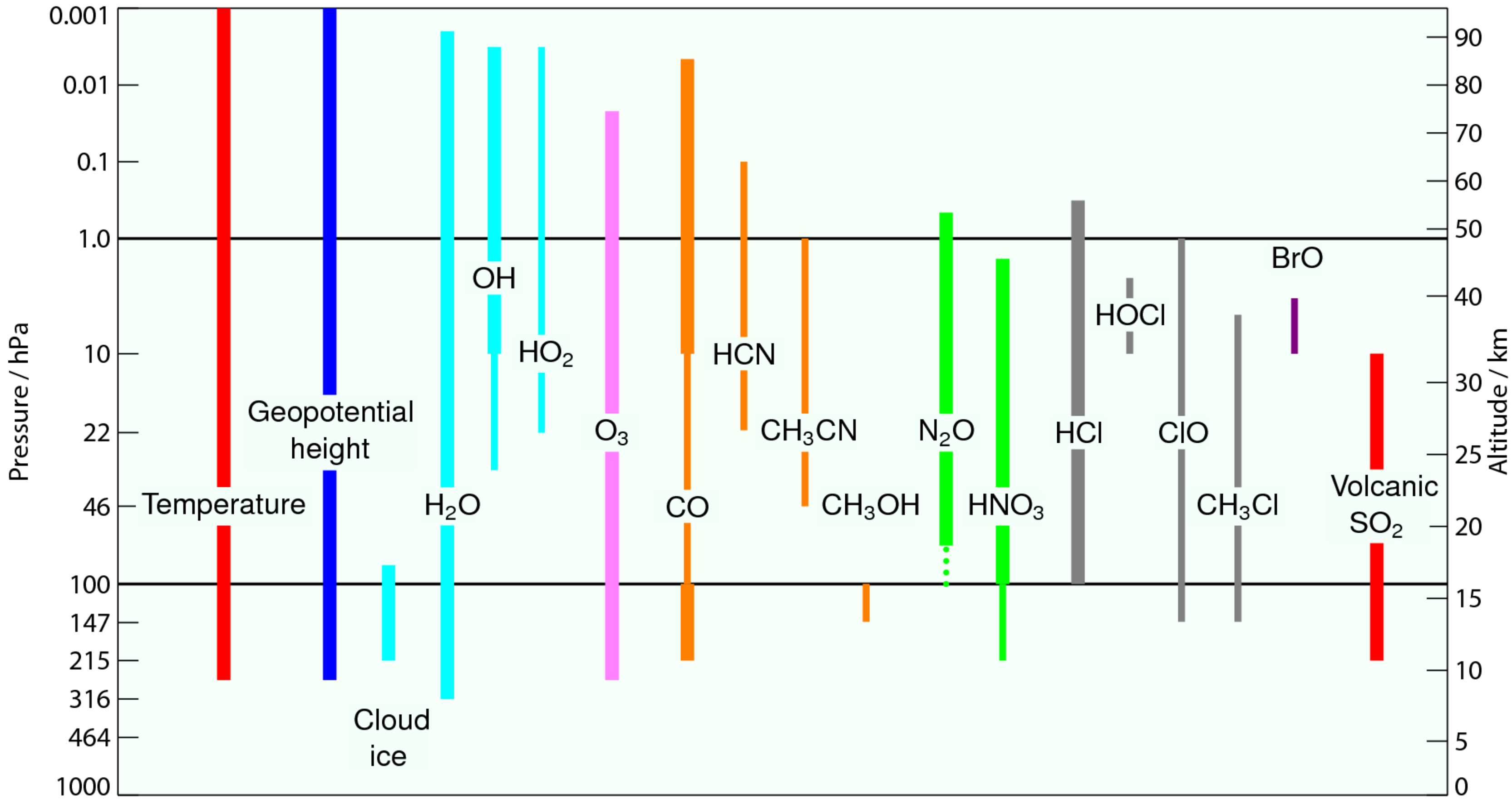
Diallo et al., ACP, 2018

Understand aspects of air pollution in the upper troposphere

Gaudel et al., Elementa Sci. Anthrop., 2018



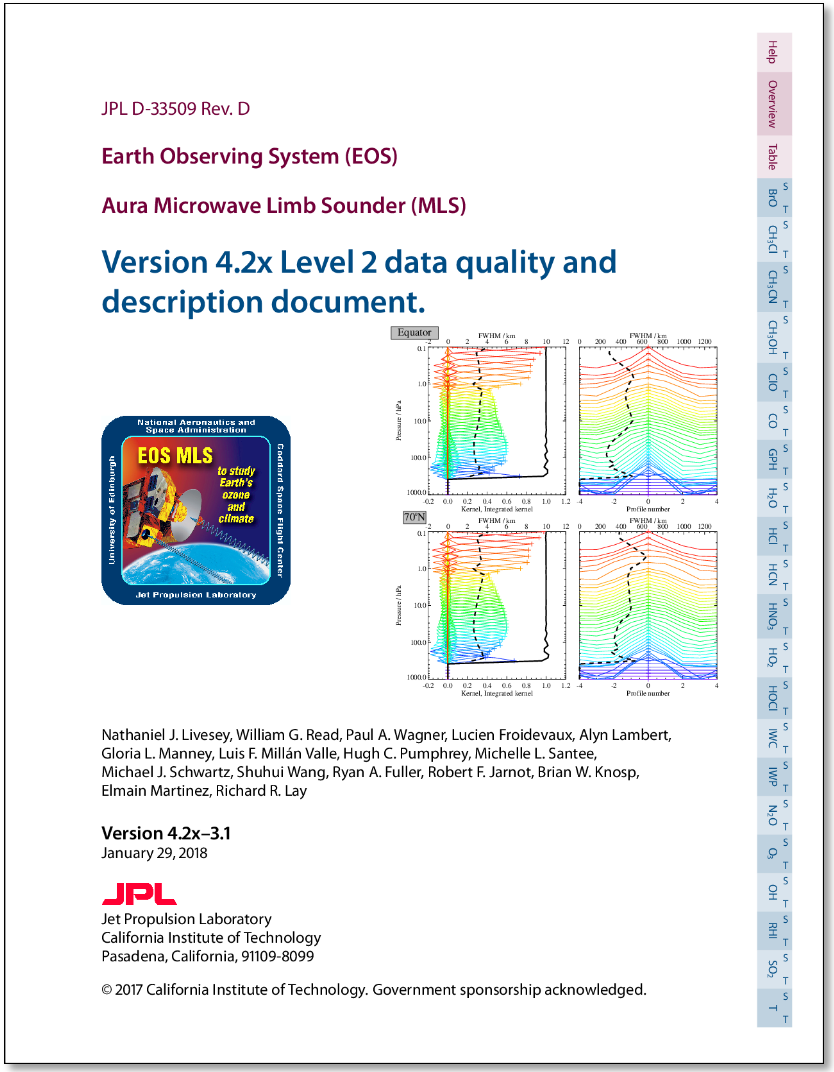
MLS data products (in version 4)



- Thinner lines indicate where averaging (e.g., weekly map, monthly zonal mean) is needed for useful signal to noise
- The dotted line for N_2O reflects a goal in MLS V5 to regain vertical range lost following the deactivation of the 640 GHz N_2O measurements

Guidelines on using MLS data

- All users of MLS data are strongly encouraged to consult the MLS data quality document
  - Current version is 4.2x-3.1, January 29, 2018
  - It includes new screening thresholds for H_2O and N_2O, as older thresholds rejected too much data in later years of mission
- Document gives guidance on formats etc.
- Plus product-specific information including:
  - Recommended vertical range
  - Typical precision, accuracy, and resolution
  - Data screening rules
  - Impact, if any, of clouds on the product
  - Any known artifacts, drifts, etc.
  - Selected comparisons to other datasets
- Users are also encouraged to contact the MLS team with any specific questions
- Particularly if the phenomenon being quantified is comparable to the precisions and/or accuracies reported


JPL D-33509 Rev. D

Earth Observing System (EOS)

Aura Microwave Limb Sounder (MLS)

Version 4.2x Level 2 data quality and description document.

Nathaniel J. Livesey, William G. Read, Paul A. Wagner, Lucien Froidevaux, Alyn Lambert, Gloria L. Manney, Luis F. Millán Valle, Hugh C. Pumphrey, Michelle L. Santee, Michael J. Schwartz, Shuhui Wang, Ryan A. Fuller, Robert F. Jarnot, Brian W. Knosp, Elmain Martinez, Richard R. Lay

Version 4.2x–3.1
January 29, 2018

JPL
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, 91109-8099

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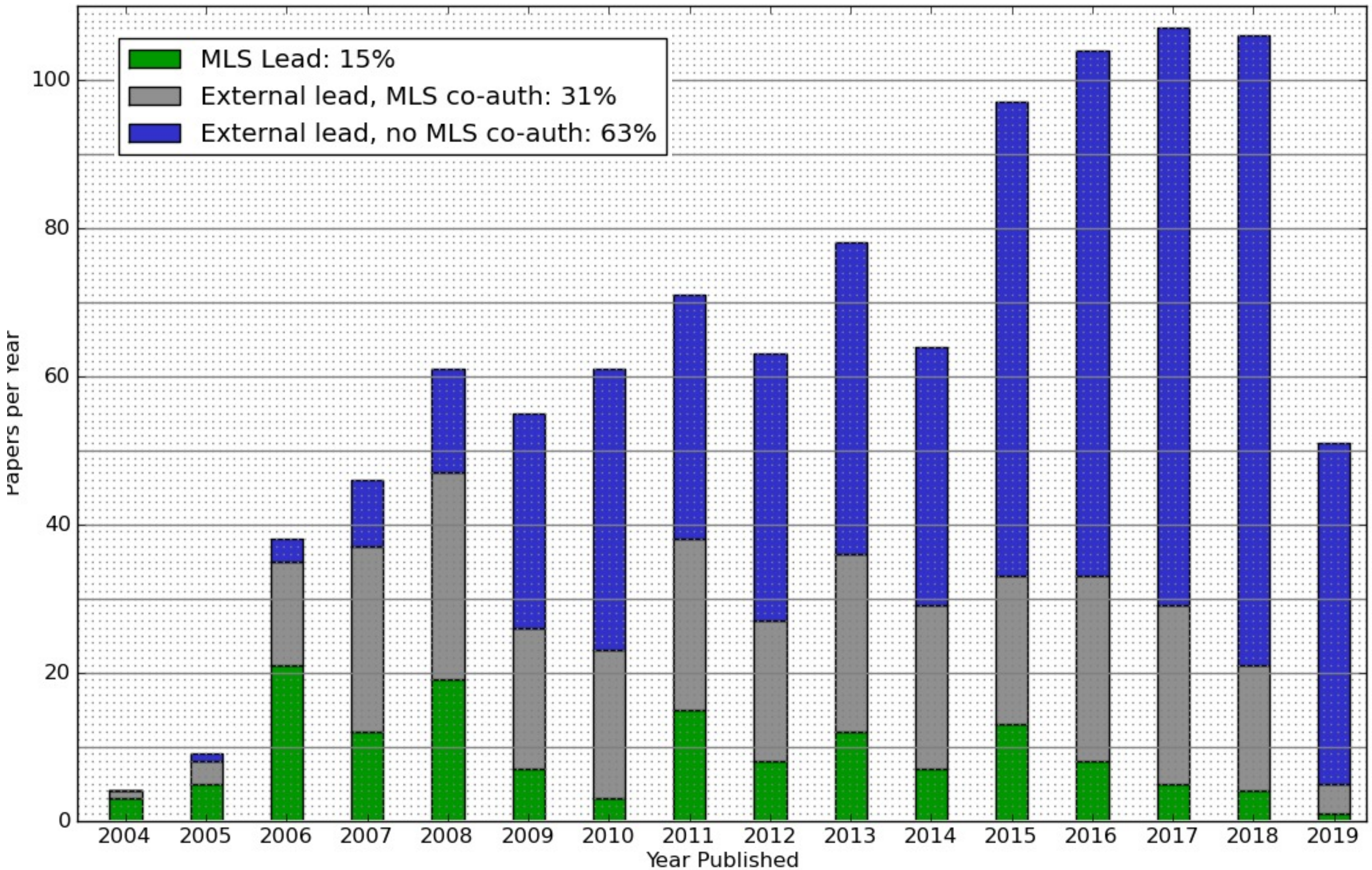
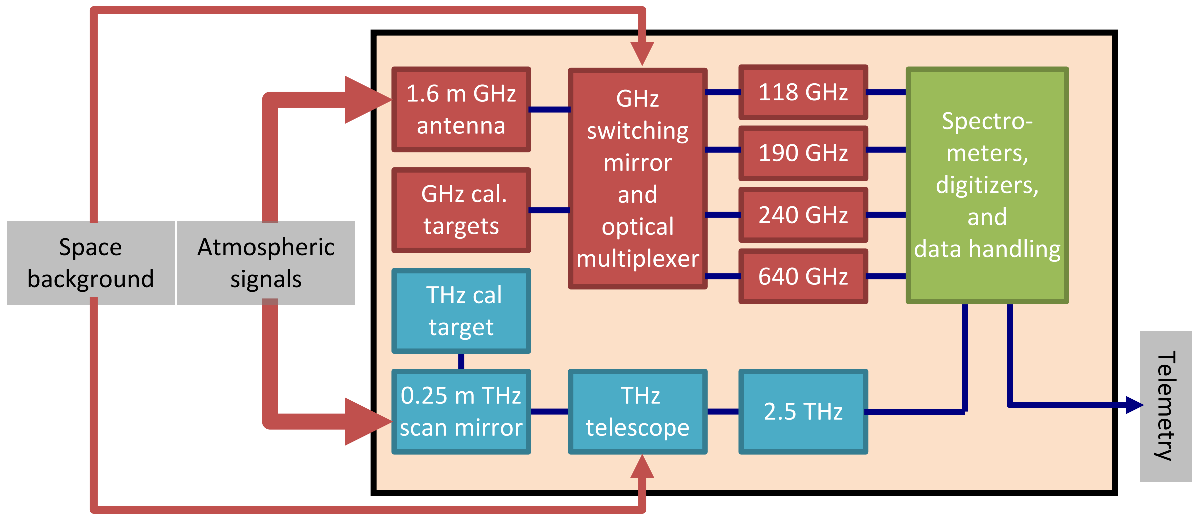
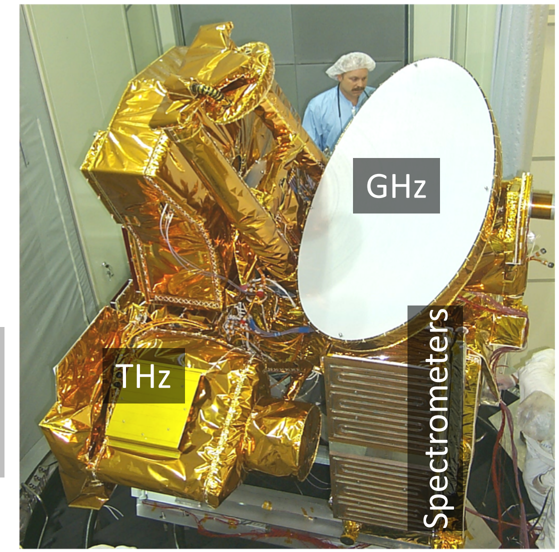
1000+ publications to date; MLS data are used more than ever!



Reminder of MLS instrument design





Receiver	Frequency	Main objectives
R1A, R1B	118 GHz	Temperature and pressure (from O_2)
R2	190 GHz	Water vapor (now also N_2O product)
R3	240 GHz	O_3, CO, HNO_3, and cloud ice
R4	640 GHz	Stratospheric chemistry
R5H, R5V	2.5 THz	Stratospheric and mesospheric OH

- MLS continues to “age gracefully”, and has generally been performing well in recent years, with no interruptions from 2012–2017
- However in 2018 and 2019 (so far), there have been five anomalies that resulted in lost or reduced days of observation

June 4 – 11, 2018: MLS "R1A" (temperature/pointing) anomaly

- On June 4th 2018, the electronics controlling "R1A", the primary 118 GHz receiver, stopped responding and was shutdown by the MLS master computer
- Following an investigation the subsystem was successfully restarted on June 11
- There are not thought to be any implications for "life expectancy"

- In principle, there is sufficient pointing information from other channels (not least from some bands in the redundant "R1B" 118 GHz receiver) to obtain useful science data
- However, MLS data processed using this alternative information would not be a "seamless drop in"; discontinuities would be expected
  - Generating such data would require a custom run of the MLS Level 2 software that would need a non-negligible amount of development, testing, and characterization
- Accordingly, as this period represents ~0.15% of the MLS dataset, we do not plan to reprocess those data at this point
  - Please contact the MLS team if you have a burning need for observations taken during this period

Other MLS anomalies in 2018/2019

June 21–25, 2018: MLS Switching mirror ("GME-B") anomaly

- On June 21st, we performed our monthly "antenna reconditioning" operation
- During the return to normal operations, the MLS switching mirror entered an anomalous state and was shut down
- Such behavior had been seen previously, and MLS returned to normal operation on June 25th
- We have updated our procedures to (a) reduce the likelihood of recurrence, and (b) enable swifter recovery should it recur

July 10–18, 2018 and January 27–31, 2019: Complete MLS instrument shutdown

- On both occasions MLS stopped communicating with Aura and was shut down
- Aura was in the "South Atlantic Anomaly" both times
- A cosmic ray hit likely confused the onboard software, which then crashed
- These were both similar to events that occurred in 2011 and 2012

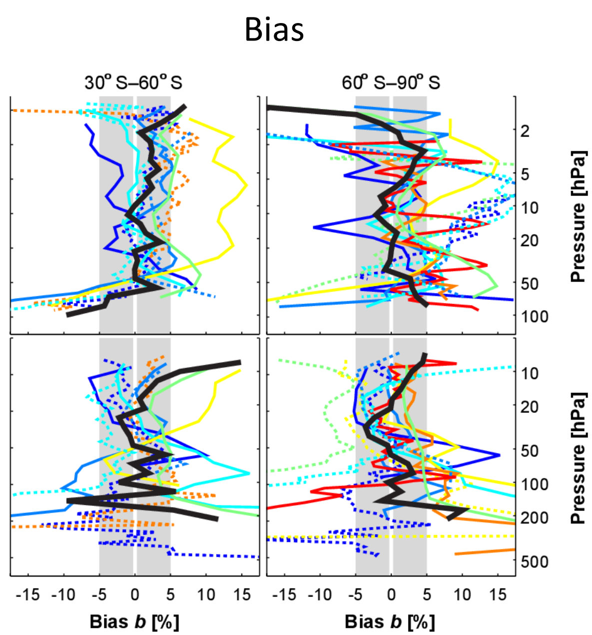
July 18–24, 2019: MLS 190 GHz receiver enters anomalous state

- Very similar behavior was seen in October 2012
- Restarting the subsystem fixed the issue

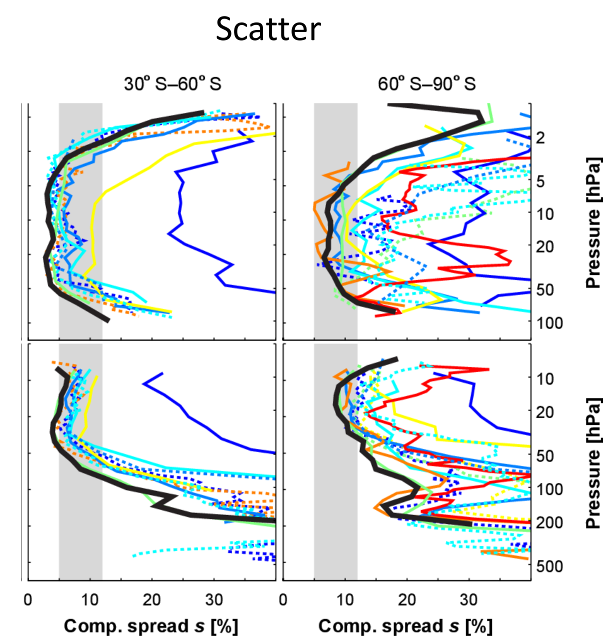
None of these anomalies have any implications for MLS life expectancy

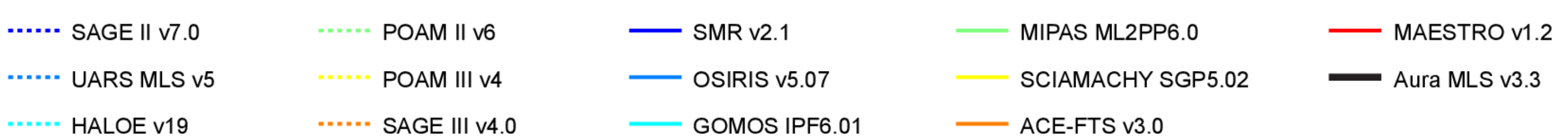
MLS ozone is the "Platinum Standard"

- MLS ozone observations agree with coincident sonde and lidar measurements better overall than those from any other satellite sounder, with smaller biases and scatter
- MLS ozone is stable to within ±1.5% decade (2004–2013) in the middle stratosphere



Bias (left pair) and scatter (right pair) between satellite ozone sensors and coincident lidar (upper) and ozonesonde (lower) measurements. MLS in thick black, other satellite sensors in various other colors and line styles. Adapted from *Hubert et al.* [*AMT*, 2016].

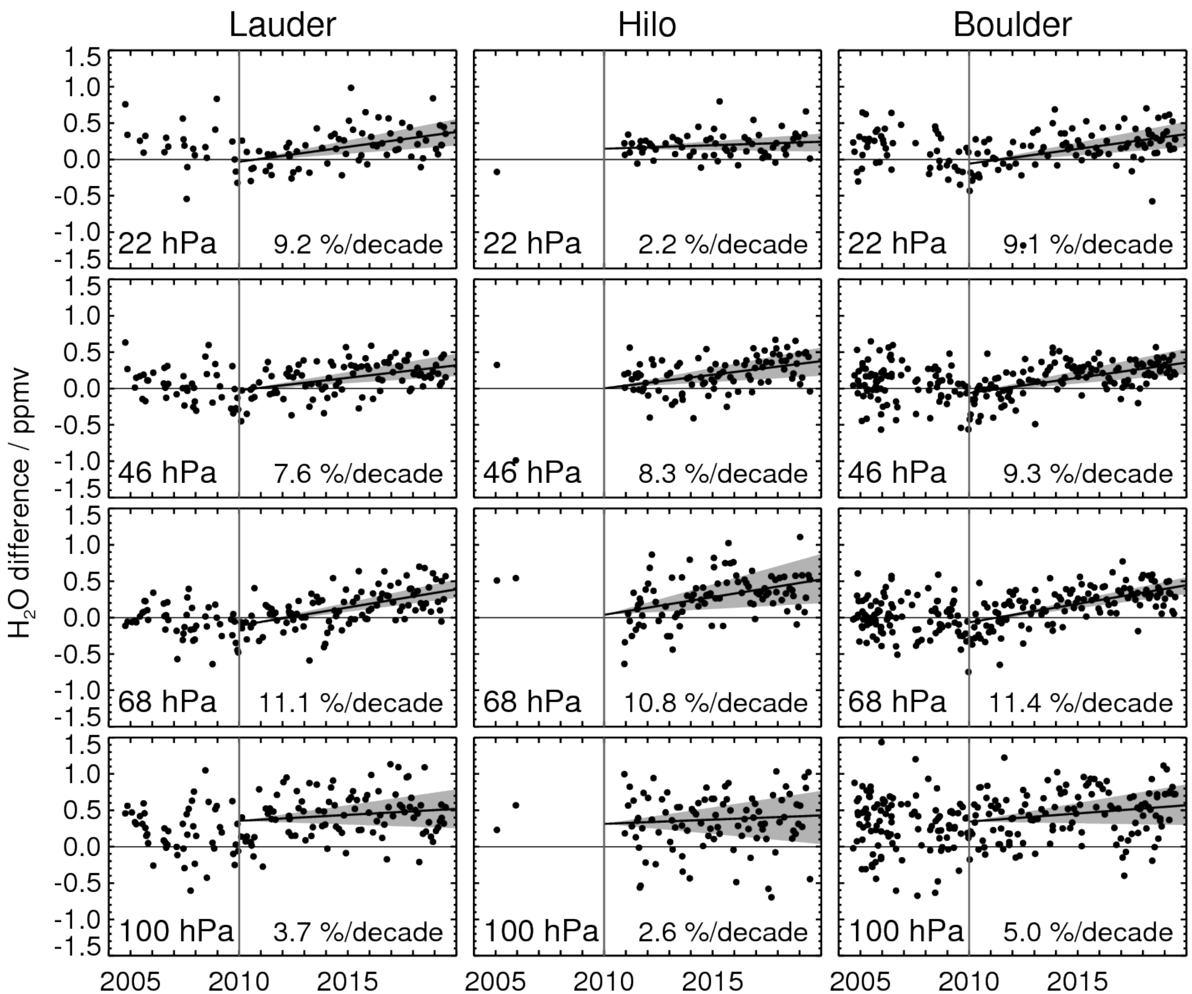




- Some in the community have publicly referred to MLS ozone as the "Platinum Standard" (the original SAGE instruments having previously been "Gold")

Indications of a drift in the MLS water vapor measurements

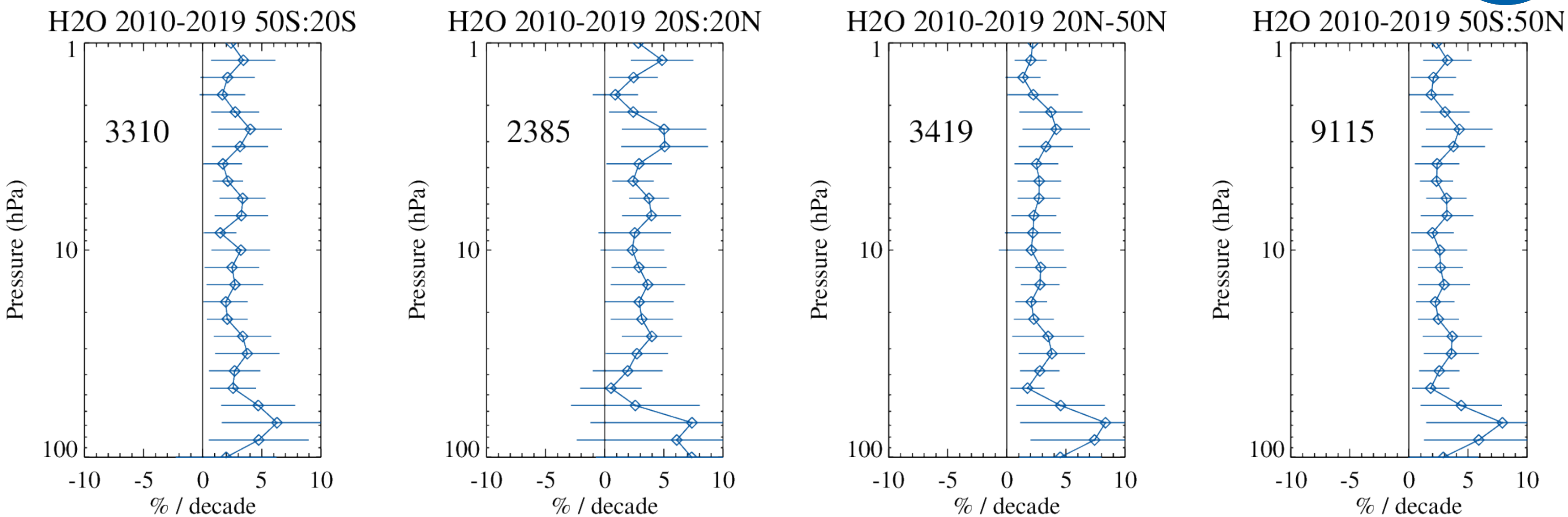
- In contrast with ozone, there are signs of drift in the MLS water vapor record, first identified in comparisons to frostpoint data by *Hurst et al.* [*AMT*, 2016]
- This drift has been the main focus of the MLS team's work in the last couple of years, and has shaped our "version 5" algorithm development work



Timeseries of differences (MLS minus sonde) between MLS water vapor and coincident frostpoint sonde observations for three sites (columns) and four pressure levels (rows).

Solid line is fitted post-2010 drift with shading showing 95% confidence (using a one-year block-bootstrap)

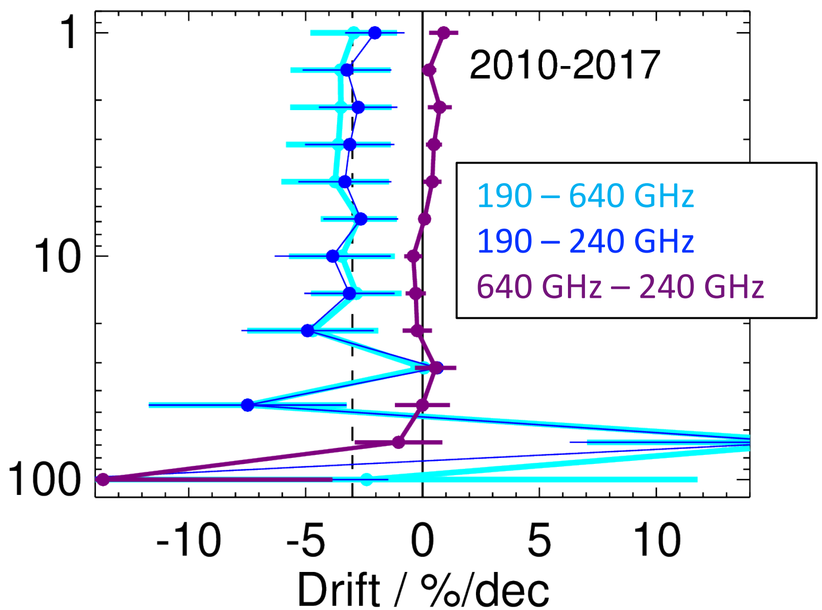
Comparisons of MLS to ACE-FTS also show a (smaller) drift



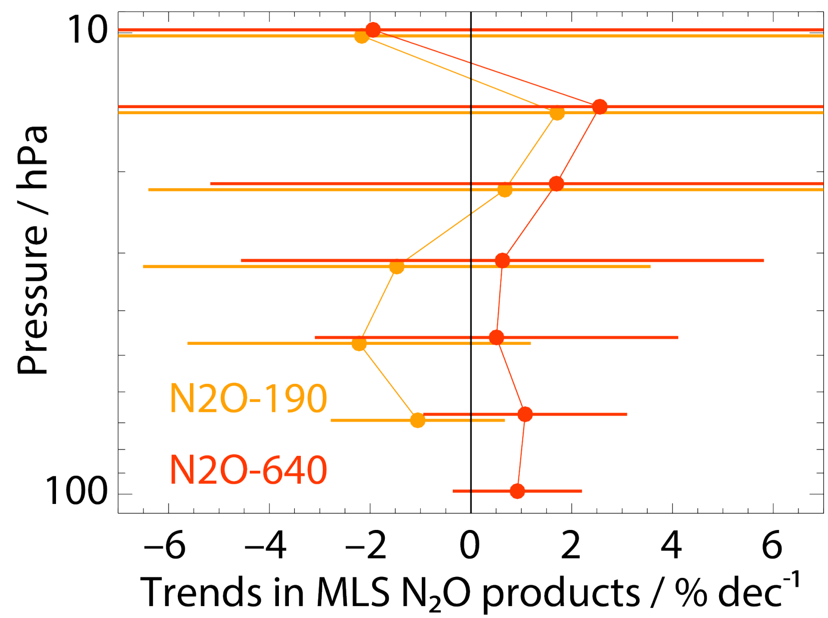
- MLS/ACE-FTS water vapor comparisons also show signs of a drift
  - Drifts at 68 hPa and greater pressures are a little smaller than those seen in frostpoint comparisons (e.g., ~7%/decade vs. ~10%/decade)
  - Higher in the stratosphere, significantly slower drifts, around ~3%/decade, are seen
- ACE-FTS is arguably the only other spaceborne instrument to have measured water vapor over this full altitude range during the same time period
  - Measurements from TIMED-SABER (for which water vapor is a newly released product) and Odin SMR are focused on higher altitudes; the SAGE-III ISS record only started in 2017
- Comparisons to ground-based microwave measurements of upper stratospheric water vapor suggest a ~5%/decade drift [*Nedoluha et al., ACP*, 2017]

Other species measured at 190 GHz are drifting too

- The MLS 190 GHz receiver, which measures H_2O, also measures:
  - N_2O (providing the "primary" N_2O product following the 2013 deactivation of the 640 GHz MLS band) and also HCN
  - O_3, HNO_3, ClO, SO_2, and CH_3CN, for which other MLS receivers provide the "primary" measurements
- Comparisons between the MLS measurements of these products from the various MLS receivers also indicate a potential drift in the 190 GHz data



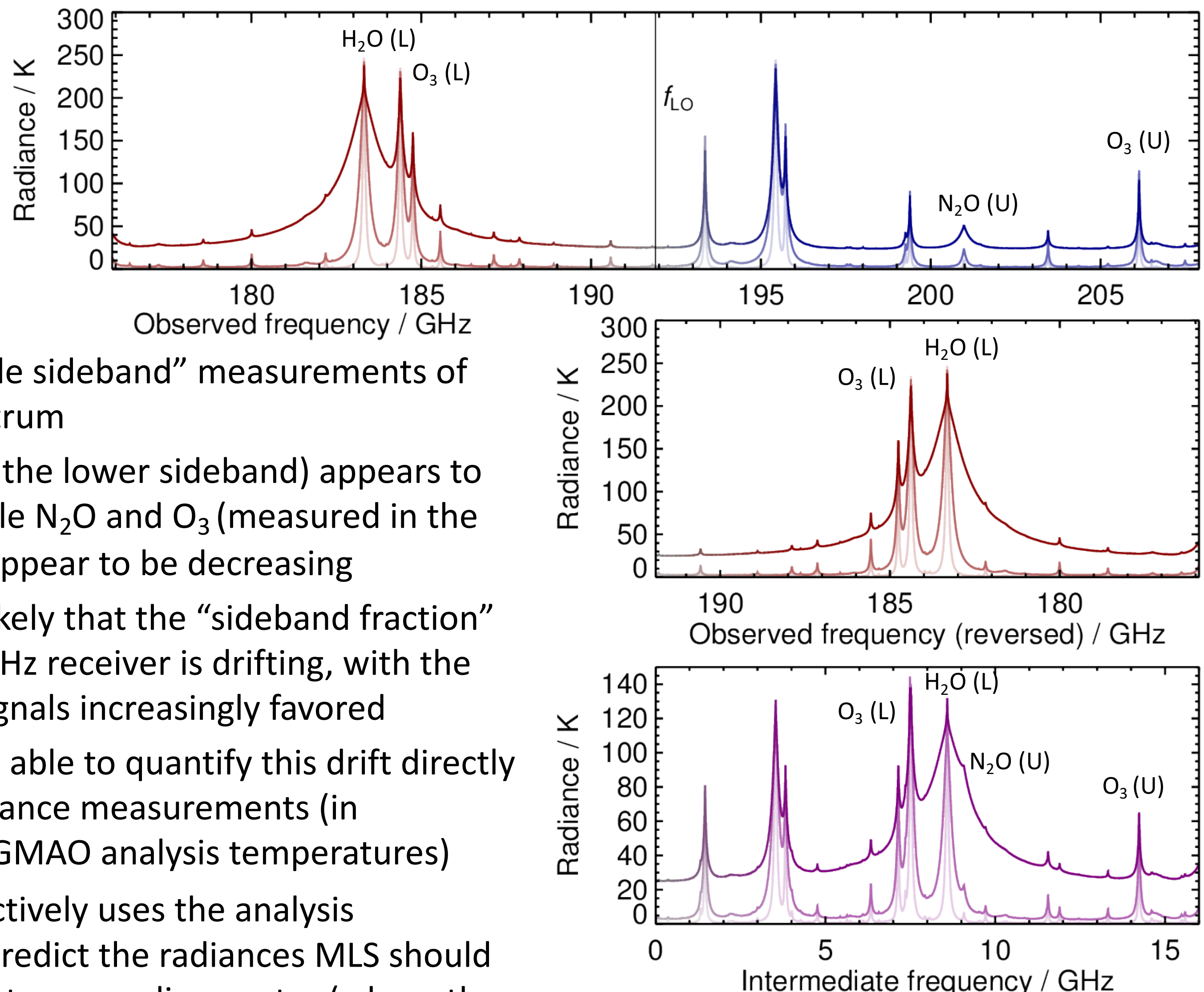
Global 2010–2017 trends in <u>differences between</u> MLS ozone measurements from the 190, 240 and 640 GHz bands



Global 2005–2013 trends in <u>MLS N_2O measurements</u> from the 190 and 640 GHz bands

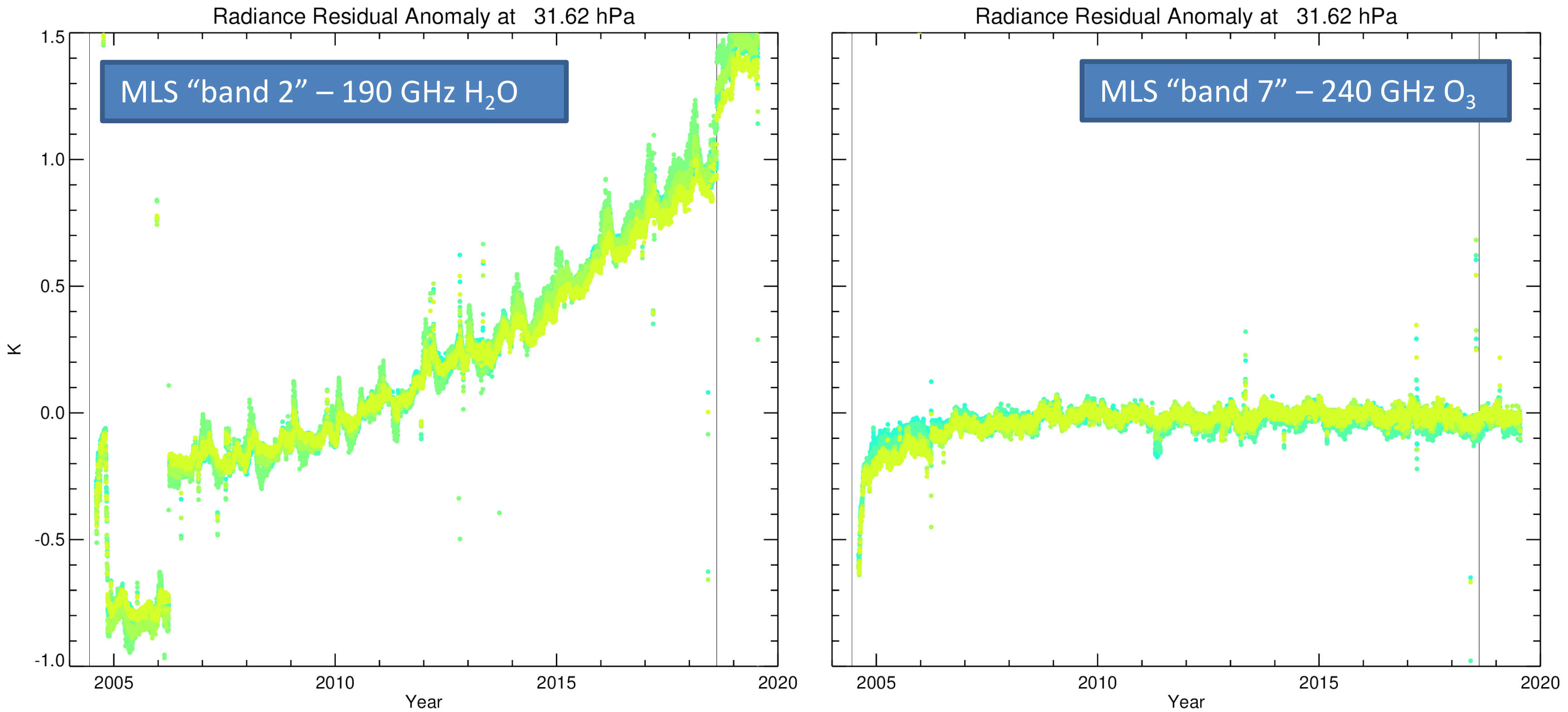
Factors potentially giving rise to these drifts

Sample 190 GHz spectra at 20 hPa (palest colors), 60 hPa, and 100 hPa (darkest colors)



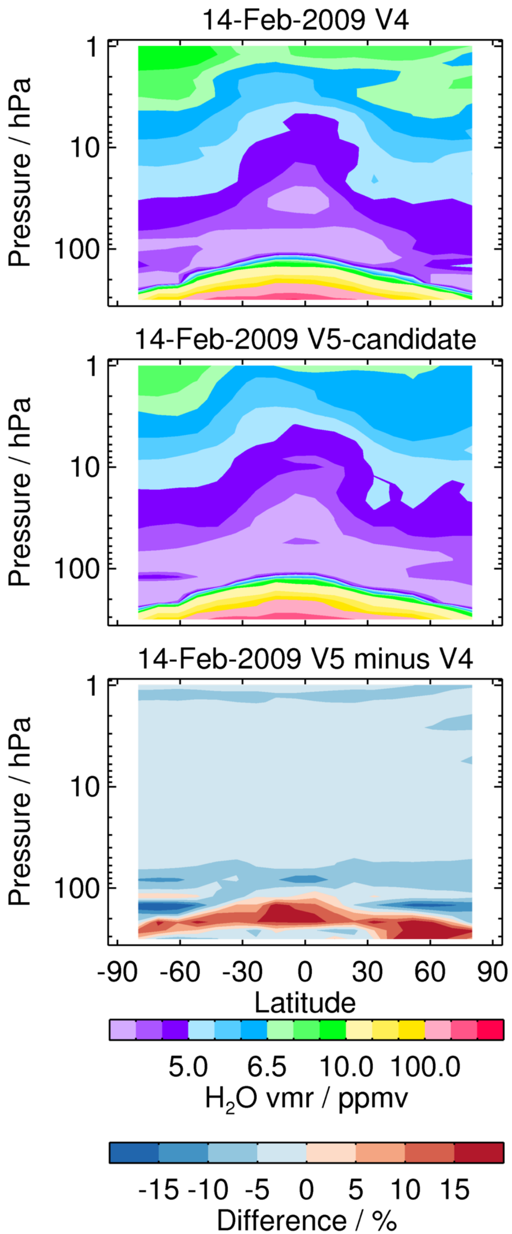
- MLS makes "double sideband" measurements of the 190 GHz spectrum
- H_2O (measured in the lower sideband) appears to be increasing, while N_2O and O_3 (measured in the upper sideband) appear to be decreasing
- Accordingly, it is likely that the "sideband fraction" for the MLS 190 GHz receiver is drifting, with the lower-sideband signals increasingly favored
- Bill Read has been able to quantify this drift directly from the MLS radiance measurements (in conjunction with GMAO analysis temperatures)
- His approach effectively uses the analysis temperatures to predict the radiances MLS should measure in the water vapor line center (where the signal is mainly one of atmospheric temperature)

Quantifying the drift in the 190 GHz sideband fractions



- The figures show the metric of the sideband fraction changes since launch for the 190 GHz water vapor (left) and 240 GHz ozone (right) bands
- We see clear signs of drift in the 190 GHz case
- The 190 GHz behavior during 2004–2006 relates to early mission changes in optical bench operating temperature
- By contrast, the 240 GHz sideband fraction is clearly very stable post 2005

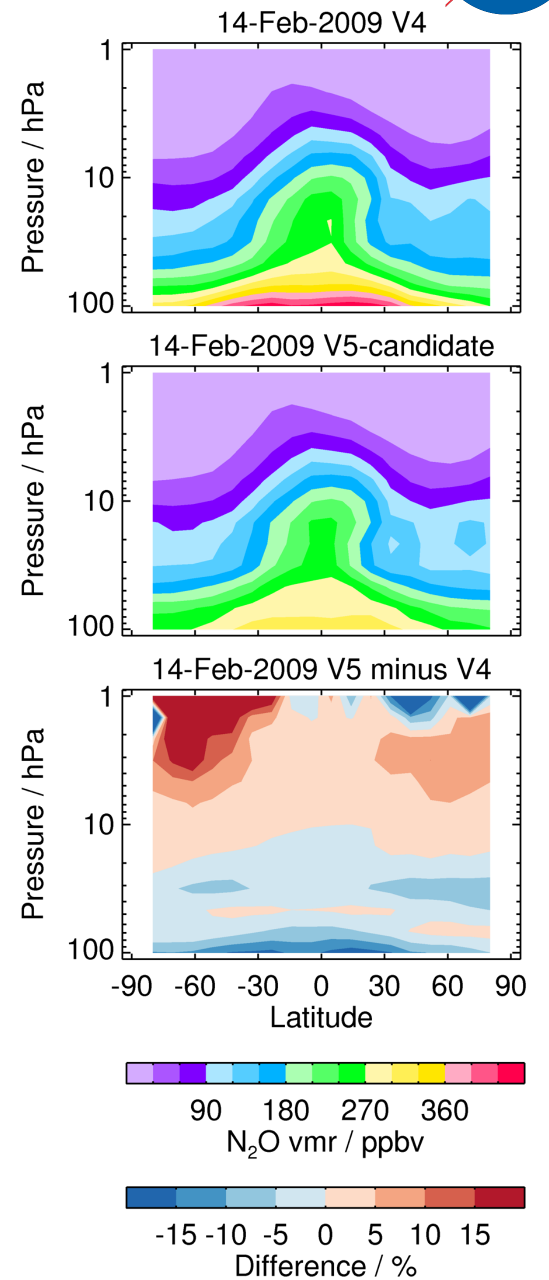
Fixing a low bias in water vapor below tropopause



- In comparisons with other sensors, MLS V4 water vapor shows a ~20% dry bias below the tropopause
- The same metric used to quantify sideband fraction change also showed it has a ~7% departure from its pre-launch calibration value
  - Again, the sideband fraction for the 240 GHz receiver (O_3, CO, etc.) agrees well with pre-launch calibration
- Additionally, we found indications of a pointing offset between the 190 and 240 GHz receivers (within the pre- and post-launch calibration uncertainty)
- Using a corrected sideband fraction, and retrieving a quasi-independent pointing for the 190 GHz receiver, brings the values below the tropopause up by a suitable amount
  - To date we have only run a few days with candidate V5 algorithms, so it is hard to be definitive
- These changes also reduce the stratospheric water vapor by ~4%, which is consistent with indications from the WAVAS-II intercomparison that V4 MLS water vapor data are slightly above the multi-instrument mean

Extending the vertical range in nitrous oxide in V5

- At launch the best MLS N_2O product was based on measurements of a line in the 640 GHz region
- However, in 2013, the MLS N_2O 640 GHz band showed signs of aging (due to a faulty component identified shortly before launch) and was deactivated
  - Other MLS 640 GHz measurements (HCl, ClO, CH_3Cl, CH_3CN, CH_3OH, BrO, HO_2, HOCl, and O_3) continue to this day
- MLS also measures a weaker N_2O line around 190 GHz
- Accordingly, to provide a consistent record, the "primary" MLS N_2O product in V4 is taken from the 190 GHz measurements
- However, the V4 190 GHz N_2O data are only useful at pressures of 68 hPa and less whereas 640 GHz N_2O had useful measurements at 100 hPa
- Work in V5 (figure on the right) has improved the data quality at 100 hPa by decoupling the water vapor and nitrous oxide retrievals
- We expect to be able to recommend V5 N_2O for scientific use down to 100 hPa



Plans for MLS version 5 reprocessing

- We have essentially completed the development of the MLS V5 software
  - We are finalizing some minor details related to climatologies and diagnostic products etc.
- We plan to deliver the new software to our production facility in a few weeks, at which point reprocessing will commence, starting with selected month-long periods
  - We will check the data from those periods to ensure that the changes are as expected
- Assuming no problems are seen, we will then continue reprocessing the entire 15-year MLS data record, and commence forward processing with V5
- The reprocessing is expected to take 1.5–2 years to complete
  - Any users wanting some periods reprocessed early are welcome to contact the MLS team

- Once the reprocessing is underway, we will turn our attention to updating the MLS quality document for V5
- When the document is finalized (early Spring 2020) the V5 data will be made public
  - Users wanting early access are welcome to contact us

- Incoming MLS data will be processed with both V5 and V4 software while the reprocessing is underway, so as to provide a contiguous record at all times
  - Some months after the V5 reprocessing is completed we will discontinue the V4 stream

New MLS "Level 3" (gridded) products to aid data use

- We are also planning to release new "Level 3" products for the first time
- These will include:

Type	Dimensions	Granularity
Daily "binned" grids	Latitude, Longitude, Pressure and Latitude, Longitude, Potential Temperature	Daily files
Daily/monthly zonal means	Latitude, Pressure, Day and Latitude, Potential Temperature, Day/month	Yearly files
Daily/monthly EqL/θ means	Equivalent Latitude, Potential Temperature, Day/month	Yearly files
Daily vortex averages	Potential Temperature, Hemisphere, Day	Yearly files

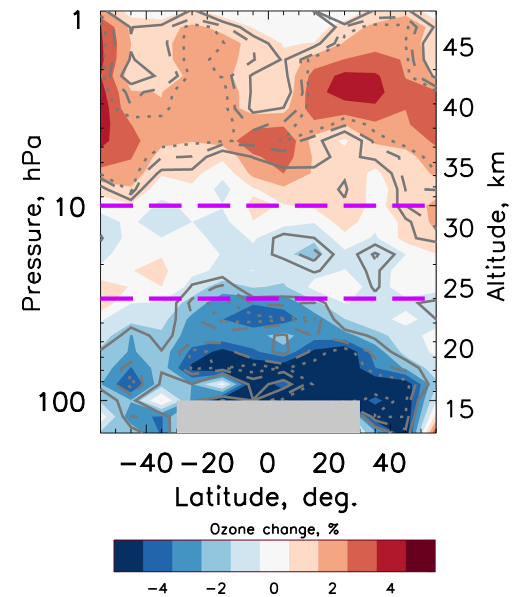
- The meteorological information used to generate the products is from MERRA-2
- For the diurnal species (e.g., ClO) the data are split into both "ascending" and "descending", and "day" and "night" averages
- All the files are stored in NetCDF
- We expect to release these for all v4 data to date this Fall, with ~monthly updates as new observations come in
- Level 3 data for Version 5 will be generated once reprocessing is completed, and updated ~monthly thereafter

MLS-related datasets and projects – GOZCARDS and MUSTARD

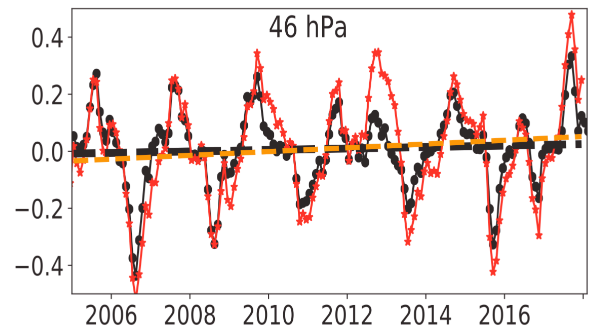
- "Global OZone Chemistry And Related trace gas Data records for the Stratosphere" (GOCARDS) is a multi-sensor multi-decade middle atmosphere composition record
  - Developed under the NASA MEaSUREs program [*Froidevaux et al., ACP,* 2015]
  - GOZCARDS data have been used in many papers (e.g., for WMO, 2018; LOTUS Report, 2018, and also in comparisons to models, e.g., *Froidevaux et al., ACP* [2019]
  - An update for ozone (GOZCARDS v2.20) was produced using SAGE-II version 7 data, and with finer vertical resolution; post-2004, this record depends only on MLS
  - These and other GOZCARDS updates are available on request (eventually from GSFC DISC)
- The SWOOSH project (Sean Davis) has similar goals, and SWOOSH and GOZCARDS are in excellent agreement
- In addition, another MEaSUREs project, "Mesospheric and Upper Stratospheric Temperature and Related Datasets" (MUSTARD), is nearing completion
  - This is generating a fused multi-sensor record of temperature and GPH profiles from UARS MLS, UARS HALOE, TIMED SABER, ACE-FTS, Aura MLS, and AIM SOFIE
  - In addition, MUSTARD will generate meteorological fields (winds, PV, etc.) derived from the Temperature and GPH fields
  - We expect delivery of the MUSTARD data this Fall
- The MLS project plans to support extension of the GOZCARDS and MUSTARD records with the latest observations for the foreseeable future

Science highlights: Ozone recovery in a changing climate

- Signs of recovery in the ozone layer are now clear in the upper stratosphere (~35–50 km)
- However, in the lower stratosphere, and in polar regions, strong interannual variability hampers detection of recovery
- For example, a recent paper [*Ball et al., ACP*, 2018] found a statistically significant decline in near-global (60S–60N) lower stratospheric ozone from 1998–2016 (upper figure)
- However *Chipperfield et al.,* [*GRL,* 2018] showed that extending the record into 2017, when MLS sees an increase in lower stratospheric ozone (lower figure), suggests a picture of strong interannual variability rather than ongoing decline
- These findings underscore the need for continued long-term vertically resolved global measurements of ozone to ensure recovery is proceeding as expected
- Ongoing measurements of other species are also needed to separate the dynamical and chemical influences on the long-term trend in ozone

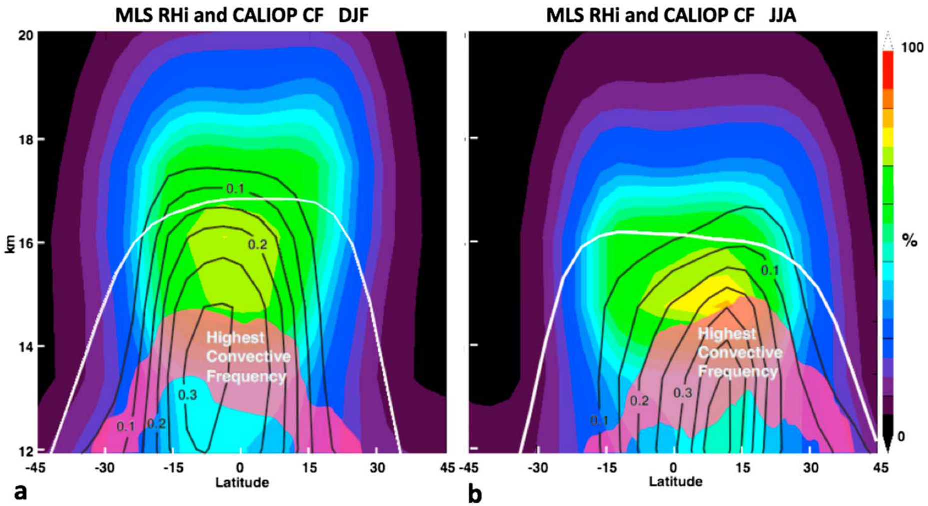


1998–2016 zonal mean ozone change from multiple satellite sensors. Note the decline found in the lower stratosphere.



MLS 46 hPa (~19 km) ozone (35–60S) showing an uptick in 2017.

Water vapor, clouds, and saturation in the TTL



MLS RHi (colors) and CALIOP CF (black contours). During DJF, the peak in RHi (about 16 km) is located well above both the highest convective frequency and the peak in CF. This suggests that convective moistening has a direct impact only in the lower part of the TTL and is less important at higher altitudes. During JJA, in contrast, the peak in RHi and peak convective frequency have a closer correspondence.

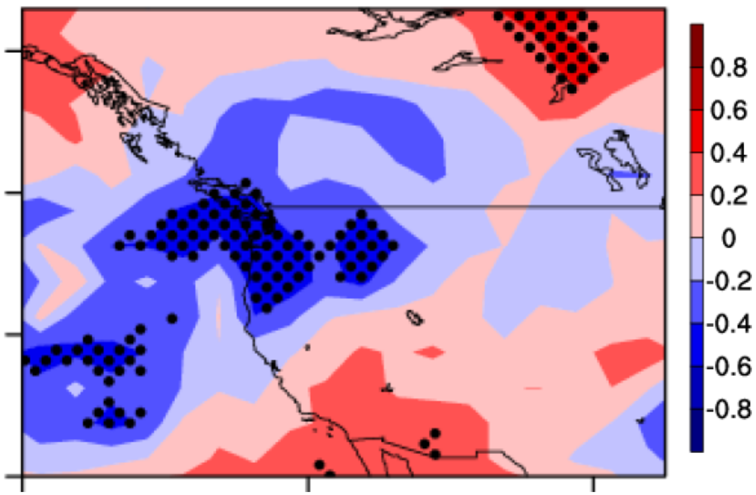
Schoeberl, M. R., et al., Water vapor, clouds, and saturation in the tropical tropopause layer, JGR, 124, 3984–4003 doi:10.1029/2018JD029849, 2019

Science Question: What processes give rise to the persistent high humidity in the Tropical Tropopause Layer (TTL,~14–16 km)?

Data & Results: A recent study used relative humidity (RHi) and cloud fraction (CF) observations from NASA's Microwave Limb Sounder (MLS) and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instruments, in conjunction with observations from NASA and other field experiments and 1D and Lagrangian models. The authors showed that the high humidity is due to both horizontal transport of air into colder regions, and slow ascent due to radiative heating, both of which lead to cloud formation. In contrast with some previous studies, the study also found that convection is not important in maintaining this high humidity environment.

Significance: The radiative impacts of water vapor, the strongest greenhouse gas, are greatest at these altitudes. Better understanding of the processes controlling the humidity of this region is essential for understanding its role in climate feedbacks and for improving climate projections.

Indications of link between Arctic ozone and precipitation



Changes in April precipitation on the US west coast are strongly anticorrelated (blue contours) with March Arctic stratospheric ozone (ozone averaged over the latitude range 60°N–90°N at pressure levels 100–50hPa). The month lag between the two variables reflects the time taken for the stratospheric circulation anomaly to propagate down to the lower atmosphere.

Ma, X. et al, Atmos. Chem. Phys., 19, 861-875, 10.5194/acp-19-861-2019

Background: Changes in stratospheric ozone can induce, via atmospheric radiation balance, stratospheric circulation anomalies. These circulation anomalies, in turn, can affect tropospheric climate via chemical/radiative/dynamical feedbacks.

Analysis: Simulations by a state-of-the-art chemistry climate model help understand a strong correlation between March Arctic stratospheric ozone (provided by the Aura Microwave Limb Sounder among other measurements) and April precipitation (provided by several satellite datasets and gauges) on the west coast of the United States. Two joint effects were identified:

- Stratospheric circulation anomalies can inhibit precipitation by producing an anomalously strong subsidence in addition to reducing the winds that typically blow from west to east bringing moisture from the Pacific.
- Arctic stratospheric ozone variations induce sea surface temperature anomalies that also can contribute to the changes in precipitation.

Significance: Arctic stratospheric ozone late winter variations could be a useful predictor of spring precipitation changes in the northwestern US. In particular, when March Arctic stratospheric ozone is anomalously high, April precipitation decreases on the west coast of the United States (mainly in Washington and Oregon states) and vice versa.

Some posters from the MLS team to look out for at this meeting

Alyn Lambert: An Overview of the Polar Processes Chapter of the SPARC Reanalysis Intercomparison Project (S-RIP) Report

Jessica Neu: Decadal-Scale Variations in Stratospheric Circulation Driven by Seasonal Timing of the Quasi-Biennial Oscillation

Gloria Manney: Understanding Extratropical UTLS Ozone Variability in Relation to the Upper Tropospheric Jets and Tropopause: Investigations using Satellite Data in Support of the SPARC OCTAV-UTLS Activity

Michelle Santee: Characterizing the climatological composition and intraseasonal and interannual variability of the Asian summer monsoon anticyclone using Aura Microwave Limb Sounder measurements

William Read: Assessment of Satellite Measurements of Upper Tropospheric H_2O

Richard Cofield: Field-of-view Characterization of the Aura Microwave Limb Sounder using Lunar Surface Radiation

Brian Knosp (presented by Valentino Constantinou): Enabling Earth Science Research Through Use of Aura MLS Data with Outside Science Data Products

Nathaniel Livesey: Why considering only "systematic error" and "random error" (or "accuracy" and "precision") can be problematic – some MLS-based examples

MLS-related posters from others

Olga Tweedy: Subseasonal variability of the upper troposphere and lower stratosphere composition during boreal summer and its relationship to Asian summer monsoon anticyclone and MJO

Karen Rosenlof: The Stratospheric Water and Ozone Satellite Homogenized (SWOOSH) database: A long-term database for climate studies

Robert Herman: Evolution of Convectively Injected Water Vapor in the Lower Stratosphere During the SEAC^{4}RS Campaign

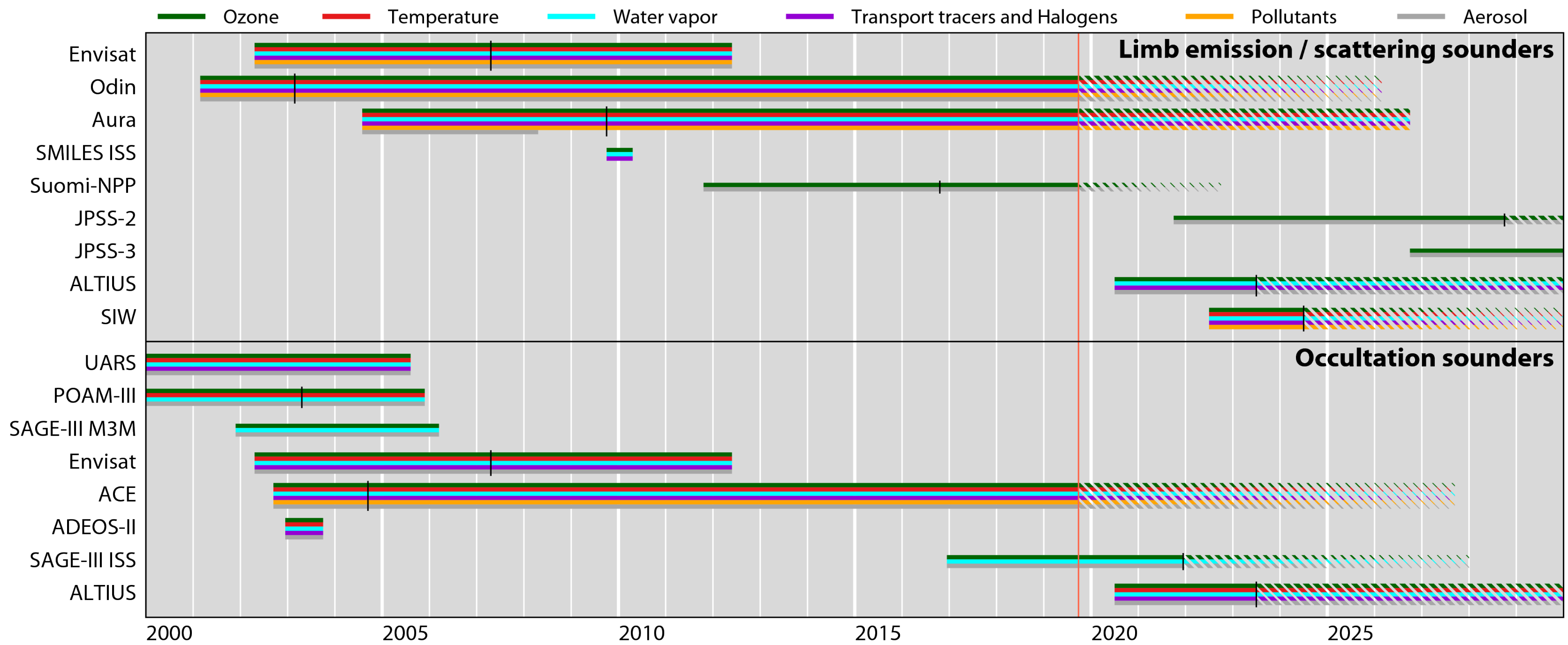
Kenneth Minschwaner: Ozone Variability in the Upper Troposphere/Lower Stratosphere: the Role of Laminae and Filamentary Structures

Mark Olsen (presented by Junhua Liu): The ENSO and QBO impact on ozone variability and stratosphere-troposphere exchange relative to the subtropical jets

Anne Thompson: Evaluation of Re-processed Ozonesonde Profiles with Aura's OMI and MLS Data

Quentin Errera (presented by Michelle Santee): Reanalysis of Aura MLS Chemical Observations

Outlook for future spaceborne middle atmosphere observations

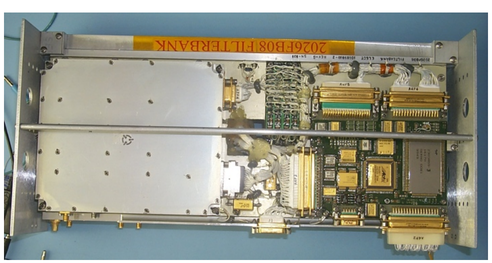


- The last 1–2 decades has witnessed a "golden age" for spaceborne observations of middle atmosphere composition, with 12 limb/occultation sounders at peak
- Aura MLS is unlikely to be operating beyond 2026
  - The local time drift starting around 2024 should not significantly impact observations
- From the USA (NASA/NOAA), the only confirmed future limb/occultation observations are ozone and aerosol from OMPS-LP on the JPSS-2 and 3 spacecraft
- Two European missions, ALTIUS and SIW, are both confirmed, but both are small instruments on experimental platforms

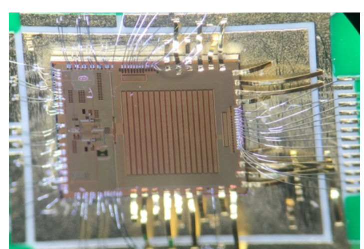
New technology for future MLS-class instruments

- New technology, largely driven by the cellphone industry, has enabled dramatic reductions in the mass and power needed for microwave technology
  - Aura MLS weighs 450 kg and used (at peak) 550 W
  - A new technology “MLS-continuity” instrument needs only 20 kg and 80 W
  - The spectrometer electronics can be much smaller too (~10 cm cube vs. ~1 m cube)
- Fundamental physics will continue to dictate the need for a fairly large aperture to provide the needed vertical resolution (the MLS primary antenna is 1.6 m tall)
- Measuring at higher frequencies (e.g., 340 GHz vs. 190 and 240 GHz), and from a lower orbit (e.g., 500 km vs. 700 km), gives better resolution for a given aperture size
- We are developing concepts for follow-on MLS instruments to fit a range of mission/instrument size profiles, including 6U CubeSat (60 cm aperture)

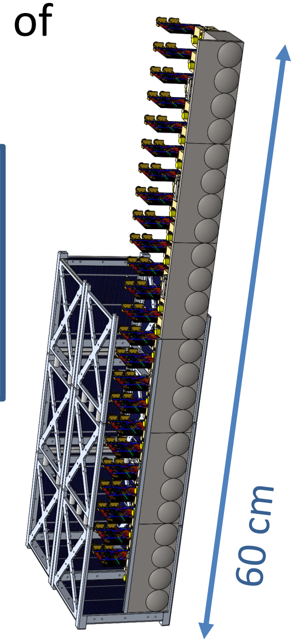
A 25-channel ~1.5 GHz spectrometer from Aura MLS, ~1.5 kg, ~40 cm



A 4096-channel 3 GHz spectrometer on a single ~5 mm chip



Concept for a phased-array based 340 GHz Microwave Limb Sounder in a 6U CubeSat form factor (12 kg, 14 W)



Summary

- MLS continues to operate well 15+ years into a five-year mission
- The instrument is "aging gracefully"
  - We expect MLS to continue operating more or less unchanged in the remaining years of the Aura mission
- The MLS 118, 240 and 640 GHz measurements appear to be as stable as ever
- There are clear signs that our 190 GHz subsystem is drifting
- The MLS "version 5" algorithms should alleviate some of that drift
- More than 1000 papers use MLS observations, with 100+ in each of the last three years

Many thanks to all those who have performed such exciting, innovative, diverse, and important scientific studies using MLS observations!